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Beth Pearson-Naul

**APPLICATION FOR UNITED STATES LETTERS PATENT  
FOR**

**AZIMUTHAL RESISTIVITY USING A NON-DIRECTIONAL DEVICE**

**BY**

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## **CROSS REFERENCES TO RELATED APPLICATIONS**

This application claims priority from United States Provisional Patent Application Ser. No. 60/409,244 filed on 9 September 2002.

## **BACKGROUND OF THE INVENTION**

### **Field of the Invention**

[0001] The invention relates to the field of measurement-while-drilling systems in a downhole environment. Specifically, the invention is a method of measuring azimuthal resistivity values taken in a measurement-while-drilling device in a downhole environment.

### **Description of the Related Art**

[0002] Measurement devices comprised of multiple transmitter and receiver arrays have been employed in prior borehole induction logging. The primary parameter of interest is the resistivity of the virgin or uninvaded formation, from which the hydrocarbon saturation of the formation is determined. Symmetric pairs of transmitters and receivers have been employed to minimize or “cancel” the effects on the resistivity measurements of rapidly changing borehole parameters such as borehole diameter, eccentricity and rugosity.

[0003] U.S. Pat. No. 4,899,112 to Clark et al. discloses a well logging technique in which

electromagnetic propagation waves are used to measure formation resistivity at different radial depths of investigation. In addition, Clark '112 teaches methods for determining the existence, location and properties of beds and caves, and also teaches a method for determining changes in the size of the borehole. These measurements are based upon the  
5 observation that phase and amplitude of apparent resistivity measurements, made at a given transmitter frequency and a given transmitter-receiver spacing, exhibit different depths of investigation. Multiple transmitter-receiver spacings have also been employed in prior art to obtain measurements into the formation of varying radial depths of investigation. Combining such measurements tends to minimize borehole effects as well  
10 as to yield information concerning the radial extent of the invasion of drilling fluid into the virgin formation. Invasion measurements can be related to the permeability of the formation which, in turn, is related to the producibility of fluids contained within the formation rock matrix. No attempts have been made in the prior art to obtain quantitative measures of physical characteristics of the borehole in conjunction with measures of  
15 electromagnetic properties of the formation. Multiple transmitter frequencies have also been applied in the prior art to enhance and separate electromagnetic properties of the formation such as resistivity and dielectric constant, obtaining varying effective radial depths of investigation and to a lesser extent to minimize borehole effects. Once again, contributions from the borehole effects have not been quantified and related to the  
20 physical condition of the borehole.

[0004] U.S. Patent No. 6,288,548, issued to *Thompson et al.*, the contents of which are incorporated herein by reference, discloses an apparatus for resistivity measurements in a

measurement-while-drilling device. The apparatus comprises a transmitting member for generating an interrogating electromagnetic field for passage through the borehole and surrounding formation. A measurement tubular is also provided which comprises a central bore which communicates with a central bore of the drillstring. Said

5 measurement tubular couples in the drillstring to locate the measurement sonde in a particular position, and to permit interrogation of the borehole and surrounding formation with the interrogating electromagnetic field. A means is provided for securing the measurement sonde in a particular location within the central bore of the measurement tubular. The measurement-while-drilling apparatus is operable in at least a transmission

10 mode of operation and a reception mode of operation, which preferably occur simultaneously. During transmission operations, the interrogating electromagnetic field is generated by the measurement sonde and radiated outward from the measurement sonde and through the measurement tubular into the borehole and surrounding formation. During reception operations, the interrogating electromagnetic field passes from the

15 borehole and surrounding formation through the measurement tubular for detection by the receiving member.

[0005] The invention of U.S. Patent No. 5,892,361, issued to *Meyer, Jr. et al.* discloses a method measuring electromagnetic parameters by detecting phase and amplitude of

20 induced signals at different receivers. Transmitters are activated sequentially at a first frequency. The phase and amplitude of the induced electromagnetic signals within the receivers are measured, yielding two measurements of amplitude and two measurements of phase shift for each transmitter activation for a total of sixteen measurements. The

procedure is then repeated at a second transmitter frequency yielding an additional two measurements of amplitude and two measurements of phase shift for each transmitter activation for an additional sixteen measurements. An apparent resistivity measurement is calculated from each of these thirty-two uncorrected "raw" measurements. Each  
5 apparent resistivity calculation, being uncorrected as previously mentioned, is greatly affected by the borehole and the near borehole environs. These raw measurements and corresponding apparent resistivity calculations are used, therefore, to determine borehole characteristics such as borehole diameter, rugosity and eccentricity as well as for correcting apparent resistivity measurements for these borehole effects. Stated another  
10 way, the invention not only provides formation resistivity measurements corrected for perturbing effects of the borehole, but also provides a method for quantifying these corrections, thereby providing useful information on the physical properties of the wellbore. These wellbore properties, in turn, can be related to such parameters as mechanical properties of the rock matrix, shallow invasion profiles, and the effectiveness  
15 of the drilling program.

[0006] The borehole instrument portion of *Meyer Jr.*, '361 comprises an elongated mandrel such as a drill collar and a measurement-while-drilling (MWD) embodiment. Two receivers comprising coils of one or more turns are wrapped around the outside  
20 diameter of the drill collar and spaced longitudinally along the center of the drill collar. Four transmitters comprising coils of one or more turns are wrapped around the outside diameter of the drill collar and are spaced symmetrically and on either side of the midpoint between the two receiver coils. However, the method of *Meyer Jr.* '361 does

not provide a resolution of resistivity values along the circumference of the drill tool.

[0007] United States Patent application Ser. No. 10/262,548 of *Fanini*, et al, discloses an induction logging tool that includes transverse coils. With the device disclosed therein,  
5 it is possible to make measurements of resistivities of earth formations that are directionally sensitive. There are several prior art patent applications and that discuss the interpretation of data acquired with such a multi-component tool. One particular application of such multicomponent resistivity tools is determination of a distance to a bed boundary in a substantially horizontal borehole. The hardware of such  
10 multicomponent tools is relatively complex, and there may be problems ensuring the relative calibration of the different components.

[0008] There is a need for a quick efficient method of resolving an azimuthal resistivity or instantaneous value of resistivities measurements. The present invention described  
15 herein meets that need.

### **SUMMARY OF THE INVENTION**

[0009] The present invention is a method and apparatus for determining a resistivity parameter of an earth formation using a non-directional resistivity logging tool within a  
20 borehole penetrating said earth formation. Measurements are made with the resistivity sensor at a plurality of rotational positions of the logging tool that are not at the center of the borehole. Measurements of a toolface angle are made using an orientation sensor such as a magnetometer. *x*- and *y*- accelerometer measurements are also made.

Deviations of the accelerometer measurements from a smooth curve (such as a sinusoid) are indicative of tool displacements from the center of the borehole. By double integration of these deviations, the tool position in the borehole can be determined. Based on the differences in the response of the resistivity sensor at different tool positions, locations and orientations of bed boundaries in the earth formation may be determined.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

10 [0010] The present invention is best understood with reference to the following drawings in which like numerals refer to like elements.

FIG. 1A (prior art) is a simplified depiction of a drilling rig, a drillstring and a wellbore equipped with an apparatus for interrogating the borehole in accordance with the present invention;

15 FIG. 1B (prior art) is a partial longitudinal section view of a measurement tubular and measurement sonde in accordance with the present invention;

FIG. 1C (prior art) is a simplified schematic view of the antenna arrangement of the measurement sonde of FIG. 1B;

FIG. 2A (prior art) depict a measurement tubular in a particular embodiment of the present invention;

FIG. 2B (prior art) depict a measurement sonde in a particular embodiment of the present invention;

FIG. 3 shows a drill tool of the invention eccentered within a borehole.

FIG. **3A** is a schematic illustration of measurements that would be made by an accelerometer on a drilling tool within a borehole.

FIG. **4** shows various examples of geological factors and the resulting effects on resistivity measurements.

5    FIGS. **5a, 5b, 5c** show regions of sensitivity of a resistivity sensor having no directional sensitivity in a borehole.

FIGS **6a, 6b** qualitatively illustrate measurements that would be made by a resistivity sensor having no directional sensitivity in proximity to a bed boundary.

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### **DESCRIPTION OF PREFERRED EMBODIMENT**

[0011] With reference to Figure **1A** , there will now be described an overall simultaneous drilling and logging system in accordance with one preferred embodiment of the present invention that incorporates an electromagnetic wave propagation (EWP) resistivity measurement system according to this invention.

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[0012] A well **1** is drilled into the earth under control of surface equipment including a rotary drilling rig **3**. In accordance with a conventional arrangement, rig **3** includes a derrick **5**, derrick floor **7**, draw works **9**, hook **11**, swivel **13**, kelly joint **15**, rotary table **17**, and drill string **19** that includes drill pipe **21** secured to the lower end of kelly joint **15**  
20    and to the upper end of a section of drill collars including an upper drill collar **23**, an intermediate drill collar or sub (not separately shown), and a lower drill collar measurement tubular **25** immediately below the intermediate sub. A drill bit **26** is carried by the lower end of measurement tubular **25**.



[0013] Drilling fluid (or "mud", as it is commonly called) is circulated from a mud pit 28 through a mud pump 30, past a desurger 32, through a mud supply line 34, and into swivel 13. The drilling mud flows down through the kelly joint and an axial tubular conduit in the drill string, and through jets (not shown) in the lower face of the drill bit. The drilling mud flows back up through the annular space between the outer surface of the drill string and the inner surface of the borehole to be circulated to the surface where it is returned to the mud pit through a mud return line 36. A shaker screen (not shown) separates formation cuttings from the drilling mud before it returns to the mud pit.

[0014] The overall system of Figure 1A uses mud pulse telemetry techniques to communicate data from downhole to the surface while drilling operation takes place. To receive data at the surface, there is a transducer 38 in mud supply line 34. This transducer generates electrical signals in response to drilling mud pressure variations, and these electrical signals are transmitted by a surface conductor 40 to a surface electronic processing system 42.

[0015] In one embodiment of the present invention, the device used by *Thompson* et al, having the same assignee as the present invention and the contents of which are fully incorporated herein by reference, may be used. As taught by *Thompson*, a measurement system embodying the present invention includes electronics contained in electronics housings contained within measurement sonde 27, shown schematically in Figure 1C, and contains elements arranged in recesses or necked-down portions of the tubular steel

housing of measurement sonde **27**. Some of these elements of measurement sonde **27** include upper transmitting antenna **29**, lower transmitting antenna **31**, and intermediate receiving antennae, **33** and **35**, which are carried about an exterior surface of measurement sonde **27**, and which are utilized to interrogate the borehole and surrounding formation. In alternative embodiments, a greater or lesser number of transmitting or receiving antennas may be utilized.

[0016] Figure **1B** depicts one embodiment of measurement tubular **25**, which includes upper, internally threaded tool joint **37** and lower, internally threaded tool joint **39**, which are adapted to couple within a drillstring, with a central section **41** disposed therebetween which is formed of a material which allows the inward and outward propagation of electromagnetic fields, to allow the transmitting antennae, **29** and **31**, and receiving antennae, **33** and **35**, of measurement sonde **27** of Figure **1C** to communicate with the surrounding borehole and formation. In accordance with the preferred embodiment of the present invention, central section **41** is formed of a material which is either "poorly-conducting" or "non-conducting". For purposes of this disclosure, semi-conductors are defined as materials which have a bulk resistivity value of greater than 0.001  $\Omega$ -meters and less than 100  $\Omega$ -meters. For purposes of this disclosure, non-conducting materials are defined as those materials which have bulk resistivity values which are greater than 100  $\Omega$ -meters. Also, for purposes of this disclosure, "good" conducting materials are defined as having a resistivity of less than 0.001  $\Omega$ -meters. Central section **41** need merely be sufficiently strong to provide mechanical strength and convey wellbore fluids, but while also allowing electrical sensors located within the interior of measurement

tubular **25** to transmit and receive oscillating electric and/or magnetic fields which are too high in frequency to penetrate the conventional prior art steel drill collars. The prior art steel collars responds to high frequency electric and/or magnetic oscillating fields by the generation of eddy currents which dissipate the field and prevent the communication inward or outward of electric and/or magnetic oscillating fields. Preferably, central section **41** may be composed of KEVLAR-based composite materials.

[0017] Using the apparatus of *Thompson et al*, (commonly called a propagation resistivity device) it is possible to make a measurement of a resistivity of an earth formation.

10 Propagation resistivity devices such as those in *Thompson* determine the resistivity using amplitude changes and or/phase shifts of the propagated signals between two spaced apart receivers. Such methods are well known and are not discussed further here.

[0018] Figures **2A** and **2B** depict measurement tubular **401** and measurement sonde **419** which is adapted to be positioned within the central bore **410** of measurement tubular **401**. Measurement tubular **401** is composed substantially of steel, as are other prior art drill collars; however, measurement tubular **401** includes four regions which include a plurality of axial slots which are disposed circumferentially about measurement tubular **401** and which extend through the width of measurement tubular **401**, but which are filled

15 with a poorly-conducting or nonconducting material, such as a KEVLAR material or such as an epoxy or ceramic material. The axial slots which are filled with nonconducting or poorly conducting material allow for the inward and outward passage of electric and/or magnetic oscillating fields, but which prevent the passage of fluid

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through measurement tubular **401**. As is shown in Figure **2A-1**, upper transmitter region **402** includes the axial slots which allow for the inward and outward passage of electric and/or magnetic oscillating fields. Likewise, lower transmitter region **407** includes the axial slots which allow for the inward or outward passage of electric and/or magnetic oscillating fields. Receiver regions **403, 405** are provided in a position intermediate the transmitter regions **402, 407**. Receiver regions **403, 405** also include the axial slots filled with poorly conducting or non-conducting material, which allow for the inward or outward passage of electric and/or magnetic oscillating fields. The regions which contain the axial slots filled with poorly-conducting or non-conducting material are separated and surrounded by solid regions **409, 411, 413, 415, and 417**, which do not allow for the passage of electrical and/or oscillating fields, since they are composed of steel which dissipates the electrical and/or magnetic oscillating field by the formation of eddy currents. Measurement sonde **419** in the depiction of Figure **2B** is disposed adjacent measurement tubular **401** in the depiction of Figure **2B**. In actual use, measurement sonde **419** is disposed within the central bore of measurement tubular **401**. Measurement sonde **419** is composed of upper transmitter assembly and pressure housing **421** which contains the upper transmitting antenna, receiver assembly and middle pressure housing **425** which contain the receiving antennas, and lower transmitter assembly and pressure housing **429** which contain the lower transmitter. Upper paddle assembly **423** and lower paddle assembly **427** are provided to centralize and position measurement sonde **413** within the central bore of measurement tubular **401**. The electrical, electronic, and data processing components which cooperate to allow for the reception and transmission modes of operation are contained within the pressure housings **421, 425, and 427**. Upper

transmitter **431** is disposed on the exterior surface of upper transmitter assembly and pressure housing **421** and is adapted to be aligned with transmitter region **402** when measurement sonde **419** is positioned within the central bore of measurement tubular **401**. Lower transmitter **437** is carried about the exterior portion of lower transmitter assembly and pressure housing **429** and is adapted in position to be aligned with transmitter region **407** of measurement tubular **401** when measurement sonde **419** is positioned within the central bore of measurement tubular **401**. Receiver antennae **433**, **435** are carried by receiver assembly and middle pressure housing **425** and adapted in position to align with receiver regions **403**, **405** when measurement sonde **419** is positioned within the central bore of measurement tubular **401**. The axial slots in measurement tubular **401** which are filled with poorly conducting or non-conducting material allow for the sonde-based measurement of well parameters outside the drillstring which would normally be impeded by the presence of a steel collar. The slots are constructed such that the collar of measurement tubular **401** maintains its structural integrity necessary for drilling operations, and drilling fluids are not allowed to flow through the axial slots since the non-conducting or poorly conducting materials are solid fluid-impermeable materials.

[0019] In an alternate embodiment of the invention, resistivity measurements are made using a prior art device such as that taught by *Meyer Jr. et al*, having the same assignee as the present invention and the contents of which are fully incorporated herein by reference. The device used by *Meyer* does not have azimuthal sensitivity, i.e., the response of the tool is rotationally symmetric. However, as discussed next, when used in

combination with a suitable standoff measuring device, measurements indicative of azimuthal variation of resistivity may be obtained.

[0020] Figure 3 shows the drill tool **455** of the present invention eccentered within a borehole **450**. During drilling, the position of the tool center **452** in relation to the center **454** of the borehole can change due to several factors, including “whirl” of the tool, which can change the direction of eccentricity. A fluid path for drilling fluid is generally indicated at **458** at the geometric center of the tool **455**. The method of the invention comprises use of a magnetometer and accelerometer, and, optionally, acoustic sensors for standoff measurements. Using the measurements made by the magnetometer and accelerometer and the optional standoff sensors, the position of the drilling tool in the borehole can be determined.

[0021] With a tool at a fixed position in the borehole and rotating at a uniform speed, an  $x$  and  $y$  accelerometer (assuming them to be centered in the tool), will generate a sine and cosine wave due to the rotation of the tool in the earth’s gravitational field.

Measurements made by the  $x$  or  $y$  accelerometers in a real drilling tool are schematically depicted in **Fig. 3A**. The abscissa is an angle of rotation of the rotating tool while the ordinate is the output of one of the accelerometers. Measurements made by an accelerometer are depicted by **471** while an idealized sine wave is shown as **473**. The deviation from the sinusoid is due to movement of the center of the tool during drilling operations. Such movement could be due to the phenomenon known as whirl. The deviations from the idealized sinusoid are residuals which are used in the present

invention for determining the position of the center of the drilling tool within the borehole.

[0022] If the rotation speed of the drillstring is assumed to be uniform, it would be a simple matter to fit a sinusoid to the accelerometer measurements. In a real world situation, the rotation of the drillstring may not be uniform. There are many reasons for the nonuniform rotation, including the so-called “stick slip” effect, variations in the torque applied to the drillstring, and the dynamics of the drillstring itself. The result of this possible non-uniform rotation is that the idealized curve from which residuals are to be measured is no longer a sinusoid. In the present invention, magnetometer measurements are used for determining the smoothing curve.

[0023] United States Patent 5564193 to *Brooks*, et al. and having the same assignee as the present invention and the contents of which are incorporated herein by reference, teaches a method for determination of a toolface orientation of a drilling sensor using magnetometer measurements. The magnetometer is proximate to the accelerometer, so that there is a constant and known relation between magnetic toolface angle as determined by a magnetometer, and a gravitational toolface angle as seen by an accelerometer. The magnetometer measurements are not responsive to the eccentric motion of the tool as long as the magnetic field seen by the magnetometers is time-invariant. This condition is satisfied as long as there are no magnetic anomalies proximate to the borehole. Hence by using the magnetometer measurements, the residuals (deviation from the smooth curve 473) can be determined. Double integration

of the residuals then gives the x and y displacements of the measurement tool from the center of the borehole.

5 [0024] As would be known to those versed in the art, double integration of accelerometer measurements can be unreliable procedure due to lack of knowledge of two integration constants (four in the present case since two accelerometers are involved). However, for the purposes of the present invention, namely determination of a relative position of a tool within a borehole, the problem is not as serious for reasons discussed next.

10 [0025] First, since the diameter of the tool is fixed, and the borehole diameter is substantially fixed, there are physical constraints on the  $x$  and  $y$  values that are obtained by the double integration. Additionally, whenever the tool becomes severely off center and hits the borehole wall, the accelerometer measurements will show sharp discontinuities or spikes. These can be used to constrain the solution obtained by double  
15 integration, or can be removed by non-linear filtering. Thirdly, the boundary value problem associated with the double integration is reduced since the sensor is rotating in the gravity field and must have an average of 1 unit over time. This bias is removed during the correlation with the magnetometer, so that only the dynamic acceleration is integrated. Finally, in an optional embodiment of the invention, a standoff sensor is used.

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[0026] Before going into how the method of the present invention is used, we discuss briefly the azimuthal variations that would be detected by a directionally sensitive resistivity sensor and then discuss the implications for the method of the present



invention using a non-directional tool.

[0027] **Figure 4** shows two prior art examples of earth models and the resulting resistivity measurements obtained with a directionally sensitive resistivity device. For a homogenous isotropic material **610**, there is no variation in measured resistivity as a directional resistivity sensor is rotated **614**. The model **612** corresponds to an azimuthally anisotropic material, as indicated by the vertical banding in the model. The model consists of two materials with densities  $\rho_1$  and  $\rho_2$ . Rotation of a resistivity sensor through  $360^\circ$  would then give a sinusoidal variation depicted by **618**: the peak values corresponding to orientations parallel to the planes of the vertical layers and the trough values corresponding to orientations perpendicular to the layers.

[0028] Turning now to **Figs 5a – 5c**, the sensitive zone for a tool inside a borehole is illustrated. In **Fig. 5a**, the tool **703** is shown at the left side of a borehole **701**. It is convenient to think of the logging tool as having a circle of sensitivity denoted by **705**. In **Fig. 5b**, the tool **703'** is on the right side of the borehole **701'** and the circle of sensitivity is denoted by **705'**. For the entire suite of possibilities of positions of the tool within the borehole, we can define an inner region **713** for which the tool is affected regardless of the position of the tool within the borehole, and an outer region defined by the annulus between the inner region **713** and the outer boundary **713** for which the effect of the resistivity of the zone depends upon the position of the tool within the borehole. Thus, if there is a bed boundary on one side of the borehole, it should be possible to define its position depending upon where within the borehole the tool happens to be.

[0029] Turning now to **Figs. 6a** and **6b**, the qualitative response of a resistivity sensor having no directional sensitivity in a borehole proximate to a bed boundary are shown. Shown in **Fig 6a** is a logging tool **803** in a borehole **801**, the center of the logging tool being displaced a distance **D** from the center of the borehole. Also shown is a bed boundary **809** between two materials **805** and **807**. Shown in **Fig. 6b** is a depiction of a measurement made by the sensor as a function of the distance **D** for the case where the material **805** has a higher resistivity than the material **807**. For larger values of **D**, the sensor is further away from the bed boundary and is affected primarily by the lower resistivity medium. For negative values of **D**, the sensor is closer to the boundary and hence sees a higher resistivity. From a knowledge of the distance **D**, and knowledge of the response characteristics of the sensor, it is possible to infer the distance from the center of the tool to the bed boundary and the resistivities of the materials **805** and **807**.

[0030] To summarize, from magnetometer and accelerometer measurements, the displacements  $x(t)$  and  $y(t)$  of the tool relative to the center of the borehole can be determined. Simultaneously, a resistivity measurement is made. When the tool is whirling at a fixed distance from the center of the borehole, if the formation has no azimuthal variation of resistivity, then the resistivity measurement made by a nondirectional tool will not depend upon the azimuth. However, if there is an azimuthal variation of resistivity in the earth formation, then this azimuthal variation in resistivity will be detected by the nondirectional tool.

[0031] A typical device for measuring azimuthal orientation can be found in CoPilot<sup>®</sup> from Baker Hughes INTEQ, which contains x-, y-, and z-accelerometers, as well as on-board signal processing capabilities. CoPilot<sup>®</sup> records and processes downhole vibrational data and can be used, for example, to obtain calculations of  $x(t)$  and  $y(t)$  values, using an azimuthal reference, which can be added using ROTAZ (rotational azimuth), to determine azimuth while rotating the drill string.

[0035] While the foregoing disclosure is directed to the preferred embodiments of the invention, various modifications will be apparent to those skilled in the art. It is intended that all variations within the scope and spirit of the appended claims be embraced by the foregoing disclosure.